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FIELD TEST OF AN IN-STACK DIFFUSION CLASSIFIER ON AN AIRCRAFT ENGINE TEST CELL

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An in-stack diffusion classifier was field tested at Tyndall Air Force Base, Florida. Particle size distribution measurements were made on the exhaust stream from the engine test cell while running a J75-P17 jet engine. Samples were collected at the test cell exhaust plane using a University of Washington in-stack cascade impactor followed, in series, by an in-stack diffusion classifier being developed at University of Florida. In addition, total particulate samples were obtained using absolute filters to determine particulate mass concentration in the exhaust gases. Opacity readings of the

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plume were also taken during sampling. The procedures to collect significant data and the general problems encountered to generate a reasonable estimate of jet exhaust aerosol size distribution using a diffusion classifier are described in this report.

PREFACE

This study was jointly funded by the Engineering and Services Laboratory, Air Force Engineering and Services Center (AFESC), Tyndall Air Force Base, Florida, and the Environmental Protection Agency's Environmental Sciences Research Laboratory (EPA/ESRL), Research Triangle Park, North Carolina. This work was accomplished under EPA Grant R-805-762-02-2. Project Officer was Captain James Tarquinio of the Engineering and Services Laboratory. The EPA project officer was Dr. Kenneth Knapp. Sample collection at Tyndall Air Force Base was performed by Dr. Dale Lundgren, Ernest Cerini, Brian Hausknecht, and David Rovell-Rixx of the Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Services (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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TABLE OF CONTENTS

Section	Title	Page
I.	INTRODUCTION	1
II.	EXPERIMENTAL PROCEDURES	2
III.	TEST RESULTS AND DISCUSSION	5
Appendix A.	Diffusion Classifier Assembly Procedure	11
Appendix B.	Run Data Sheets with Weight Gain Results	16
Appendix C.	PET Computer Printout and Program for Diffusion Classifier Data Reduction	25

LIST OF FIGURES

Figure	Title	Page
1	Frequency Histogram for Run No. 3 Using D_{p50} Method	9
2	Cumulative Log Probability Distribution for Run No. 3	10

LIST OF TABLES

Table	Title	Page
1	Sampling Point Grid for the Outlet of J75 Engine Test Cell Parameters	3
2	Calculation Results for Run No. 3	7
3	Average Smoke Opacity Readings at J75 Engine Test Cell	8

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SECTION I

INTRODUCTION

An in-stack diffusion classifier was field tested at Tyndall Air Force Base, Panama City, Florida. Particle size distribution measurements were made on the exhaust stream from the engine test cell while running a J75 P17 jet engine. Field sampling took place from 2-4 September 1980. It was again attempted on 9-11 September 1980.

The particle size distribution of the J75 jet engine exhaust was measured using a University of Washington in-stack cascade impactor followed, in series, by an in-stack diffusion classifier recently developed at the University of Florida. In addition, total particulate samples were obtained using absolute filters to determine particulate mass concentration in the exhaust gases. Whenever possible, opacity readings of the plume were also taken during sampling.

During the first testing period (2-4 September 1980), sampling was performed on a J75 engine, serial #610497. This type of engine has a thrust of 13,000 pounds at military power. The engine was tested at operating conditions from 80 to 100 percent power. Testing had to be terminated on 4 September 1980 because the engine was needed on the flightline. No other engine was available for testing at the time, so the test team left Panama City.

Data collected during the first sampling period was not sufficient to generate a reasonable estimate of the jet exhaust aerosol size distribution. The general problems encountered are discussed in Section II, Test Procedures.

A second sampling session was attempted 9-11 September 1980. However, due to engine test scheduling problems, beyond the control of testing personnel, no engine was available to test. Despite efforts to locate a suitable engine, none was available. While waiting for a test engine, numerous quality checks were performed by the test team to assure that weighing and handling techniques were not biasing the measurements in any way. The checks completed and the results obtained are discussed in Section III.

On 11 September 1980, it was learned from the Air Force personnel in charge of engine testing that there was little chance of receiving an engine in time to test that week. A decision was then made to abort the testing. The test team returned to Gainesville.

SECTION II

TEST PROCEDURES

The outlet of the test cell was measured and then traversed for gas velocity and temperature along 5 of its 15 channels. The measurements were done at 80 percent power. The data was averaged to obtain values for calculating nozzle size and selecting a suitable sampling point. The measured data along with averages are given in Table 1. A 1/4-inch-diameter nozzle was chosen as the closest available to the ideal diameter calculated at 0.17 inch. The sampling point chosen was 42 inches into channel No. 8. This sampling point was used throughout the entire set of runs.

University of Washington Impactor substrates were prepared and conditioned at 350°F in the Gainesville laboratory prior to transport to the test site. Coatings used for each test run are listed on the data sheets (Appendix B).

All weighing was done on site in laboratory space supplied by the Air Force. Substrates were weighed immediately prior to use on a Cahn electrobalance. The impactor and diffusion classifier were then immediately assembled with the tared substrates. Assembly of the diffusion battery is described in Appendix A. The University of Washington Impactor was assembled according to manufacturer's specifications.

In addition to the impactor and diffusion classifier, the sampling apparatus included an EPA Method 5 type meter box. Several stainless steel Gelman filter holders, with appropriate size glass fiber filters, were also used for the total particle samples.

The selected nozzle was attached to the inlet of the impactor. The impactor was followed by the diffusion classifier, stainless steel pipe, flexible tubing, condenser unit, and the EPA Method 5 meter box.

After the equipment was moved to the test cell scaffolding, the inlet of the impactor was plugged and the sampling unit placed into the hot gas stream for heating to gas stream temperature. After a 30-minute warm-up period, during which time a total particulate matter filter sample was obtained, the diffusion classifier assembly was unplugged and run. Normal testing time was 30 minutes, but this was shortened to 15 minutes at 100 percent power to prevent strain on the jet engine. The diffusion classifier assembly was run with the meter box vacuum gauge set at 17 inches of mercury. This allowed the matched critical orifices in the diffusion classifier to go critical and thus maintain a constant flow through the sampling system. Field data sheets are included for each run in Appendix B.

At the end of the run, the equipment was returned to the on-site laboratory for weighing. While still hot, the diffusion classifier was disassembled. This was done in an effort to eliminate sticking of the fiber filters to metal parts of the stages.

TABLE 1. SAMPLING POINT GRID FOR THE OUTLET OF J75 ENGINE TEST CELL

Channel No. / Inches into Channel	13	10	8	6	3	
	190	190	185	180	200	Temperature (°F)
6	0.95	0.56	0.41	0.46	0.65	Velocity (in. H_2O)
	200	190	180	185	200	Temperature (°F)
12	1.4	1.3	1.6	1.5	0.98	Velocity (in. H_2O)
	200	200	190	190	200	Temperature (°F)
18	1.1	1.5	1.9	1.6	1.1	Velocity (in. H_2O)
	200	200	195	200	200	Temperature (°F)
24	0.99	1.3	1.5	1.5	0.99	Velocity (in. H_2O)
	195	205	200	200	205	Temperature (°F)
30	0.76	1.1	1.2	1.3	0.90	Velocity (in. H_2O)
	205	210	200	205	210	Temperature (°F)
36	0.64	0.85	0.90	1.0	0.80	Velocity (in. H_2O)
	205	210	200	205	210	Temperature (°F)
42	0.58	0.65	0.75	0.85	0.64	Velocity (in. H_2O)
	210	210	210	210	210	Temperature (°F)
48	0.49	0.33	0.56	0.65	0.54	Velocity (in. H_2O)
	210	210	210	210	210	Temperature (°F)
54	0.38	0.10	0.28	0.48	0.40	Velocity (in. H_2O)
	210	210	210	210	210	Temperature (°F)
60	0.05	0.10	0.11	0.07	0.05	Velocity (in. H_2O)

Average Temperature = 205 °F

Average $\sqrt{\Delta p}$ = 0.855

The diffusion classifier filters were then weighed along with the impactor stage substrates. The weight gains were calculated for each particle collection stage and then used to construct the exhaust gas particle size distribution. Several problems were encountered which prevented reliable size distribution data from being generated.

One significant problem was filter material being lost due to sticking to the metal housing surfaces. This problem was most prevalent when the stages were allowed to cool before disassembly. Several solutions were tried, including disassembly while hot and the use of teflon® backup filters. The teflon® backup filters seemed to help, but the diffusion classifier still required disassembly while hot. In Run No. 8, the diffusion classifier was not disassembled while hot because the sampling procedure was being filmed by Air Force personnel. This was time consuming and allowed the stages to cool.

A major problem encountered was the low smoke level from the J75 engine. The largest filter weight gain was only about 0.3 milligram in Run No. 6, where no filter sticking was in evidence. Handling and weighing precision checks completed during the second test week showed diffusion classifier stage weight gain deviation of ± 0.03 milligram. Therefore, the largest measured weight gain was only ten times the variation due to handling, assembly, disassembly, and weighing. More ideal stage weight gains would be on the order of 1 milligram. In an attempt to reach this, the power setting of the engine was increased from 80 percent to increase the smoke emissions. However, this increase in power caused an increase in the engine's operating temperature so the sampling time could not be extended and risk engine damage. During Run No. 8 at 100 percent power the test had to be shortened because the gas temperature increased so much that the water-cooling jets were about to be activated (normal engine test procedures).

Several possible solutions exist for the low filter weight gain problem. Running at a low power setting for a very long period would increase the weight, but with a substantial increase in fuel consumption. A different type of test engine could be used which creates more smoke. One solution might be to de-tune an engine specifically to create more smoke for testing purposes.

During the second sampling trip, 9-11 September 1980, no engine was available for testing. However, it was thought one would become available so the sampling team remained on site.

Quality control checks were performed by the sampling team. Checks included: running clean, filtered air through the diffusion classifier and determining the filter weight differences; repeated weighings of individual filters after removal; duplications of filtered air runs; Cahn balance calibration checks; and repeated simple assembly-disassembly runs to check for technique problems. The results indicated that the technique of assembly and disassembly give filter weight change values that are ± 0.03 mg.

Finally, a run was set up with an absolute glass fiber filter preceding a teflon® filter to check the effect of clean, hot stack gas on the tefon® filter. This run was to be coupled to a diffusion classifier run using only teflon® filters in the classifier. This check was never completed because a test engine was not available.

SECTION III

TEST RESULTS AND DISCUSSION

Weight gain results and other relevant data have been tabulated for each test run. This information is presented in Appendix B.

As stated in Section II, several problems occurred during the sampling and analysis which rendered most of the diffusion classifier data unusable for the calculation of size distribution. Of the four diffusion classifier runs completed, only Run No. 3 yielded data which could generate a reasonable distribution. An assumed weight gain was necessary for D.C. stage No. 5. This allowed a distribution to be calculated.

Using weight gain information in Appendix B, calculations were made for a normalized weight distribution within the size intervals covered by the impactor and the diffusion classifier. A cumulative log probability distribution was also calculated for Run No. 3.

The size distribution was calculated using the D_{p50} method for both the impactor and the diffusion classifier. The values calculated for each size interval are listed in Table 2. The normalized weight distribution values were used to generate a frequency histogram (Figure 1). The cumulative log probability distribution was plotted in Figure 2.

Analysis of diffusion classifier data by the D_{p50} method gives only a rough approximation of the size distribution of very small particles. A more refined method is being developed to use a nonlinear iterative formula. This generates a distribution taking into consideration the gradual slope of the diffusion classifier size cutpoint curve. The data from Run No. 3 was used in a computer program using this formula. This program is currently being examined and refined to maximize its reliability. The distribution output and the actual program used are presented in Appendix C.

Opacity measurements taken during sampling followed EPA Method 9 guidelines as far as location of observer, location of sun, direction of plume travel, etc. These measurements were not taken continuously at 15-second intervals. Only an approximate opacity measure was of interest for this study. As expected, opacity tended to increase as engine stress was increased, as shown in Table 3. This increase of opacity coincided with an increase in particulate grain loading in successive runs.

The size distribution of the aerosol in Run No. 3, the only reliable run, appears to be bimodal. The log probability plot (Figure 2) shows an S-shape which indicates a bimodal condition. This is even more clearly illustrated in the normalized histogram (Figure 1). This figure shows a major peak around 0.1 to 0.2 micrometer and a minor peak around 3 micrometers. The large peak is probably the primary combustion aerosol which is typically submicron in size due to the nature of origin. The minor peak is probably due to reentrainment of particle agglomerates. These are usually larger than one micron and few in number. This produces a significant fraction of weight in the micron range of sizes. However, as shown in Figure 2, over 80 percent of the aerosol weight is due to particles in the submicron range. Again, this is shown in Figure 1 where the area of the histogram below one micron is substantially larger than the area above one micron. It should be noted that the ratio of the area under a given size interval to the area of the total distribution is a direct measure of the ratio of size interval weight to total particulate weight. This information is useful in the design of effective control equipment.

Further field work is necessary to solve existing sampling problems as well as discover and solve additional problems. Also, additional work is needed on the data reduction program for the diffusion classifier to obtain reliable and accurate distribution of submicron aerosols.

TABLE 2. CALCULATION RESULTS FOR RUN NO. 3

D_{p50} (μm)	Wt (mg)	Wt/Vol (mg/m^3)	$\frac{\Delta Wt}{V \Delta \log D_p}$	%<D_p
31	0.05	0.14	0.28	97
14	0.06	0.16	0.46	94
5.2	0.03	0.08	0.19	92
2.6	0.15	0.41	1.36	83
1.5	0.07	0.19	0.80	79
0.74	0.07	0.19	0.62	75
0.38	0.05	0.14	0.48	72
0.27	0.15	0.41	2.76	63
0.14	0.60	1.62	5.68	29
0.069	0.25	0.68	2.21	15
0.041	0.15	0.41	1.81	6
0.01	0.10	0.27	0.44	

$\Sigma wt = 4.70$ mg/m^3

TABLE 3. AVERAGE SMOKE OPACITY READINGS AT J75 ENGINE TEST CELL

Run No.	Process Rate Percent Power	Pounds/hr.	Average Opacity Observed (%)	
1	80	3000	NA	
2	80	3000	5	Black
3	80-90	4980	15	Black
4	90	NA	NA	
5	95	7500	NA	
6	95	7500	25	Black
7	100	12000	32	Black
8	100	12000	27	Black

NA = Not Available

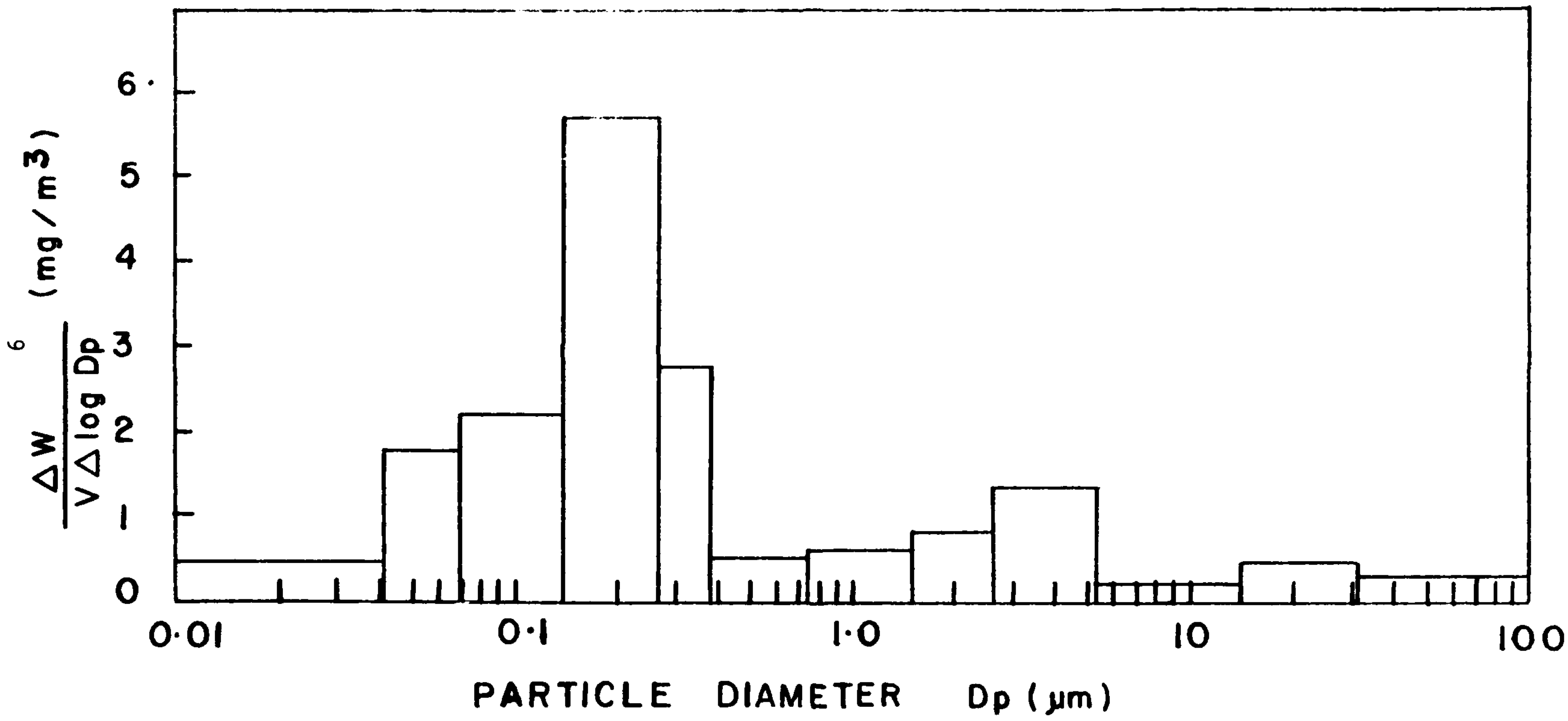


Figure 1. Frequency Histogram For Run No. 3 D_{p50} Method

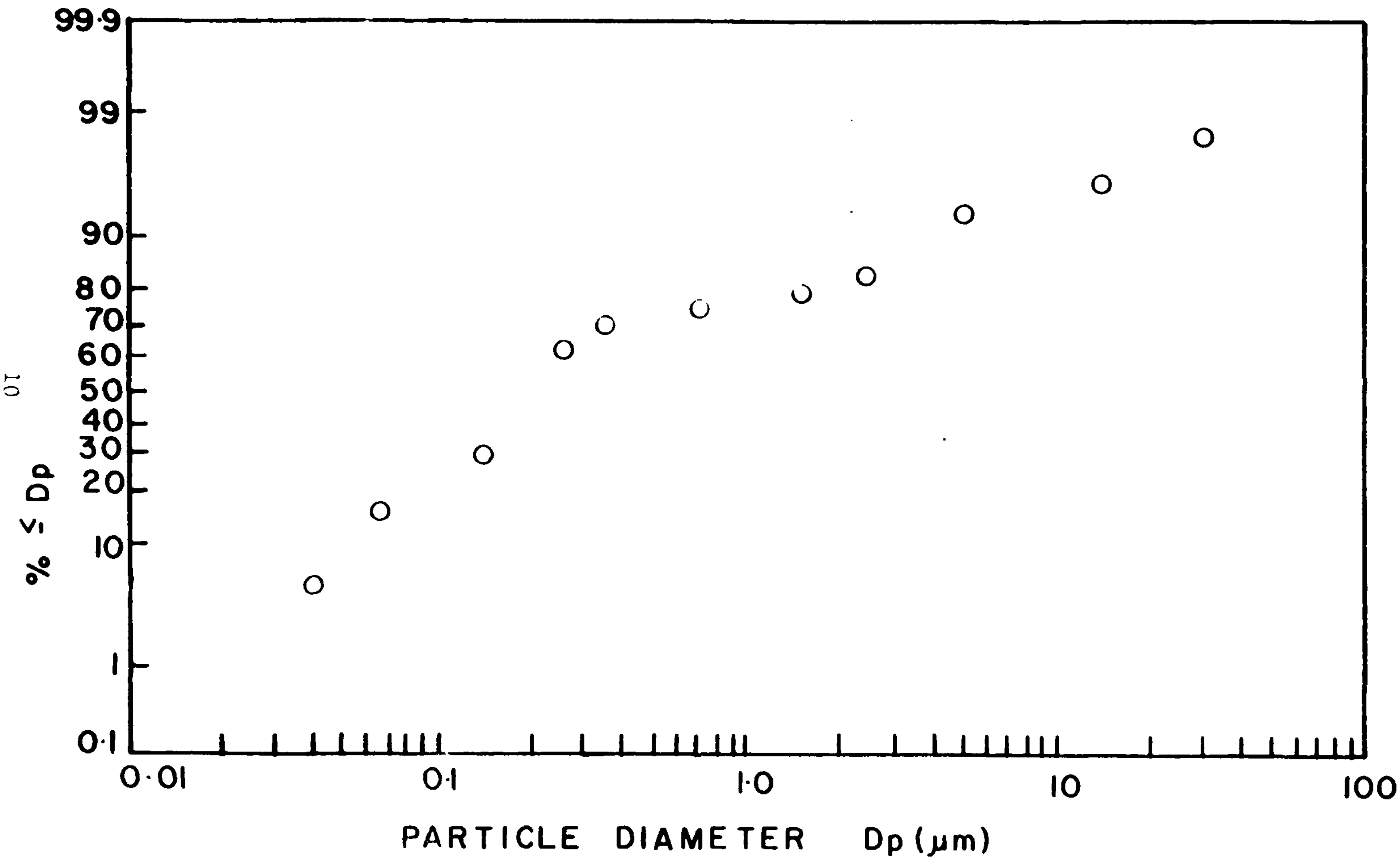


Figure 2. Cumulative Log Probability Distribution for Run No. 3

APPENDIX A

DIFFUSION CLASSIFIER ASSEMBLY PROCEDURE

Figure A-1(a) shows the major sections of the diffusion classifier. The following diffusion classifier assembly procedure is recommended:

1. Clean all surfaces thoroughly.

2. Clean orifices in acetone or other solvent and make sure they are not plugged. The orifices should not require frequent cleaning. Yet, they should at least be checked after each ten hours of operation. It is a good practice to occasionally check their calibration.

3. Apply a high temperature lubricant to all threaded parts if operating conditions warrant it. Care must be taken in applying the lubricant to the various diffusion classifier stages and orifices. This helps reduce filter sample contamination and plugging of orifices by the residues of the high temperature lubricant after the volatile components have vaporized.

4. Thread the orifices snugly into the Swagelok fittings and the Swagelok fittings into the base. To avoid problems at elevated temperatures, do not overtighten the fittings in the base [Figure A-1(b)].

5. Precondition five filters in an environment as similar as possible to that being sampled, and choose filters with temperature limits compatible with that of the gas being sampled. Weigh these filters and record their weights.

6. Place the filter over the perforated plate and fine mesh screen filter support, and then place the seal ring on top of the filter in the bottom section of each diffusion classifier stage. Filters must be handled carefully to keep spurious weight losses or gains to a minimum. Place clean, unplugged screens in the top section of each stage, and then insert the retaining ring. Avoid using sharp instruments like screwdrivers in this operation because of the risk of damaging the screens. Now assemble the top and bottom sections of each of the five stages [Figures A-1(c), (d), and (e)]. Stage No. 5 has no screens, and stage No. 4, No. 3, No. 2, and No. 1 have 5, 10, 20, and 36 screens, respectively. The number of screens can be varied as needed. To check for screen plugging, use a low power microscope. If a significant buildup is observed, the screens should either be replaced or cleaned and reused. Frequency of cleaning depends on the operating conditions. As a general rule, the screens at the upstream end should be checked after every test. At the first sign of plugging, the screens should either be cleaned, or the first few screens from the upstream end should be replaced.

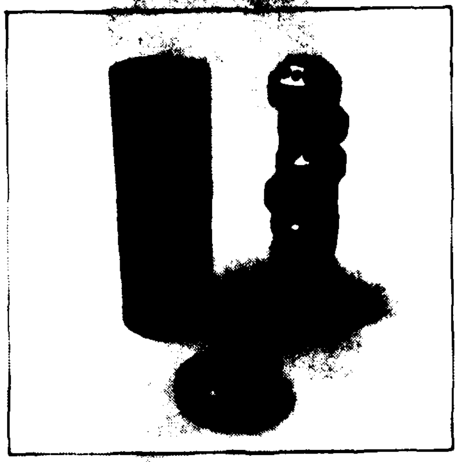
7. Attach the diffusion classifier stages to the base in the following order:

a. Stage No. 5 is secured to Swagelok fitting No. 5 at the center of the base [Figure A-1(f)].

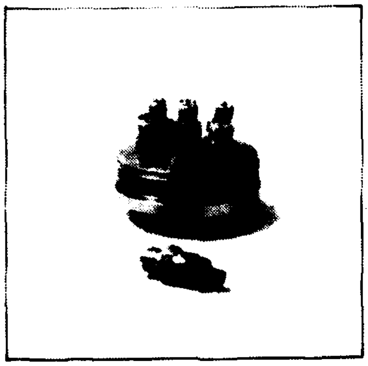
b. Stage No. 4 and No. 3 are secured to their respective fittings; No. 4 and No. 3 are located directly opposite each other [Figure A-1(g)].

c. A similar procedure is followed with stage No. 2 and No. 1 [Figure A-1(h)].

8. Secure the cylindrical casing and inlet section in place. The diffusion classifier is now ready for sampling [Figure A-1(i)].



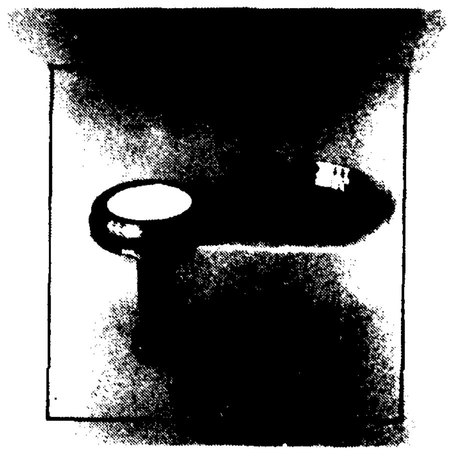
(a) The major sections of the diffusion classifier



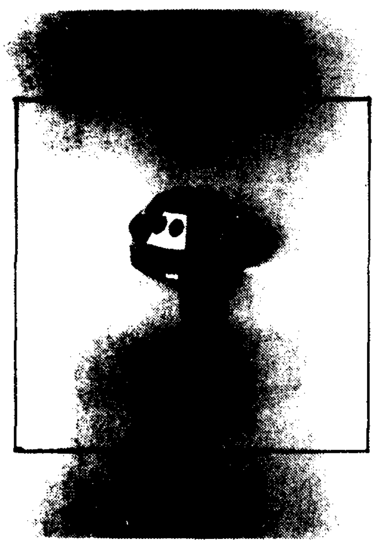
(b) Orifice, Swagelok fitting, and base assembly

Figure A-1. Diffusion Classifier Assembly Procedure

(c) Diffusion Classifier Stage
completely disassembled

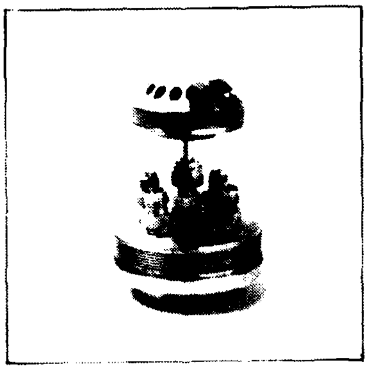


(d) Diffusion Classifier Stage
partially assembled

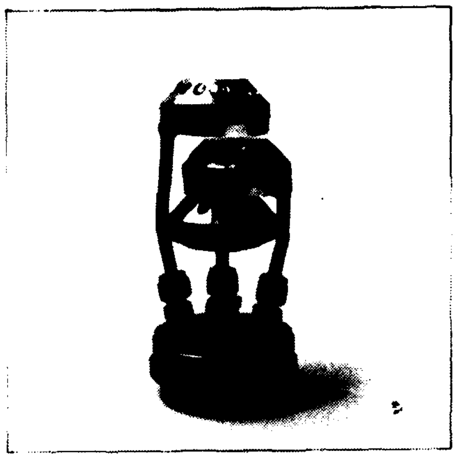


(e) Diffusion Classifier Stage
fully assembled

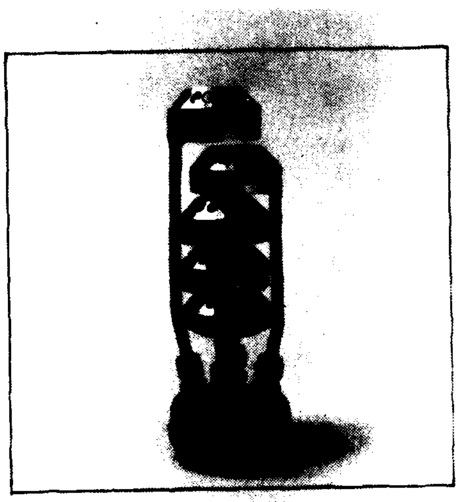
Figure A-1. Diffusion Classifier Assembly Procedure (Continued)



(f) Assembly of diffusion classifier stage No. 5 to Swagelok fitting No. 5



(g) Assembly of diffusion classifier stages No. 4 and No. 3 to Swagelok fittings No. 4 and No. 3



(h) Assembly of diffusion classifier stages No. 2 and No. 1 to Swagelok fittings No. 2 and No. 1

(i) Diffusion classifier fully assembled

Figure A-1. Diffusion Classifier Assembly Procedure (Concluded)

APPENDIX B

RUN DATA SHEETS WITH
WEIGHT GAIN RESULTS

Field Data Run No. 1

	SAMPLING CONDITIONS:
TEST LOCATION Tyndall Air Force Base J75 P17 Engine Test Cell	Temperature 675°R (215°F)
TEST TYPE Impactor/Diffusion Classifier	Pressure ambient
DATE September 2, 1980	H_2O concentration 3.1%
TIME 1450	Molecular weight 29
SAMPLED VOLUME 12.50 DSCF	Sampled volume 16.37 acf
PROCESS RATE 80% Power 3000#/hr.	Sampling time 30 min

PARTICULATE WEIGHT GAIN

Impactor: University of Washington Coating: Apiezon L

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	ΔW/VΔ Log d_p (mg/m^3)
1	31	666.63	666.63	0.00	-
2	14	974.66	974.75	0.09	-
3	5.2	970.95	970.92	-0.03	-
4	2.6	979.99	979.97	-0.02	-
5	1.5	989.50	989.45	-0.05	-
6	0.74	1007.80	1007.74	-0.06	-
7	0.38	988.89	988.85	-0.04	-
Impactor Sum (> 0.38 μm)					

Diffusion Classifier: A Filter Media : Glass Fiber

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	ΔW/VΔ Log d_p (mg/m^3)
1	0.27	139.55	139.76	0.21	-
2	0.14	140.24	140.31	0.07	-
3	0.069	139.32	139.46	0.14	-
[illegible]	[illegible]	140.12	140.12*	0.00	-
5	<0.041	140.05	140.22	0.17	-
Diffusion Battery Sum (< 0.38 μm)				0.85	-

TOTAL weight collected in run ____________

Concentration ____________

____

*Note: small amount of this filter stuck during removal.

Field Data Run No. 2

SAMPLING CONDITIONS:

TEST LOCATION Tyndall Air Force Base

Temperature 653°R (193°F)

TEST TYPE Single High-efficiency filter

Pressure ambient

DATE September 3, 1980

H_2O concentration 2.6%

TIME 0910

Molecular weight 30

SAMPLED VOLUME 16.20 SCF

Sampled volume 20.80 acf

PROCESS RATE 80% Power 3000#/hr.

Sampling time 20 min

PARTICULATE WEIGHT GAIN Gelman Filter

Impactor:

Coating:

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	ΔW/VΔ Log d_p (mg/m³)
1		137.26	138.13	0.87	-
2					
3					
4					
5					
6					
7					

Diffusion Classifier:

Coating:

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	ΔW/VΔ Log d_p (mg/m³)
1					
2					
3					
4					
5					

TOTAL weight collected in run ______ mg

Concentration 1.898 mg/dscm³

______ grains/dscf

*Note: This filter ran immediately prior to Run No. 3 during same engine .

Field Data Run No. 3

SAMPLING CONDITIONS:

TEST LOCATION Tyndall Air Force Base

Temperature 676°R (216°F)

TEST TYPE Impactor/D.B.

Pressure ambient

DATE September 3, 1980

H_2O concentration 2.6%

TIME 0935

Molecular weight 29

SAMPLED VOLUME 13.04 DSCF

Sampled volume 17.61 acf

PROCESS RATE 80-90% 4980#/hr.

Sampling time 30 min

PARTICULATE WEIGHT GAIN

Impactor: University of Washington

Coating: Apiezon L

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	ΔW/VΔ Log d_p (mg/m³)
1	31	680.73	680.78	0.05	0.28
2	14	975.39	975.45	0.06	0.46
3	5.2	981.27	981.30	0.03	0.19
4	2.6	986.22	986.37	0.15	1.36
5	1.5	991.45	991.52	0.07	0.80
6	0.74	995.98	996.05	0.06	0.62
7	0.38	979.52	979.57	0.05	0.48
Impactor Sum (>0.38 μm)				0.48	

Diffusion Classifier: A

Filter Media : Glass Fiber

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	ΔW/VΔ Log d_p (mg/m³)
1	0.[illegible]	139.57	139.60	0.03	2.76
[illegible]	0.[illegible]	138.38	138.53	0.15	5.68
3	0.069	140.71	140.91	0.20	2.21
4	0.041	137.96	138.19	0.23	1.81
5	<0.041	140.18	140.20	0.11 (2)	0.44
Diffusion Classifier Sum (<0.38 μm)				1.25 (2)	

TOTAL weight collected in run 1.73 mg

Concentration 4.69 mg/dscm³

grains/dscf

(1): Filters stuck to both steel backing plate and spacing rings in all D.C. stages.

(2): Assumed value. Stage 5 weight gain in error Therefore: assumed = 0.25 mg Total gain of 5 x 0.25 = 1.25

Field Data No. 4

TEST LOCATION Tyndall Air Force Base	SAMPLING CONDITIONS:
TEST TYPE Single high-efficiency filter	Temperature 677°R (217°F)
DATE September 3, 1980	Pressure ambient
TIME 1408	H_2O concentration 3.2%
SAMPLED VOLUME 8.52 SCF	Molecular weight 30
PROCESS RATE 90% Power	Sampled volume 12.04 acf
	Sampling time 10 min

PARTICULATE WEIGHT GAIN: Gelman Filter

Impactor: Coating:

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{ Log } d_p$ (mg/m^3)
1		138.53	139.08	0.55	
2					
3					
4					
5					
6					
7					

Diffusion Classifier: Coating:

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{ Log } d_p$ (mg/m^3)
1					
2					
3					
4					
5					

TOTAL weight collected in run ______ mg

Concentration 2.281 mg/dscm ^{3}

______ grains/dscf

*Note: This filter run immediately prior to Run No. 5 during same engine ....

Field Data Run No. 5

SAMPLING CONDITIONS:

TEST LOCATION Tyndall Air Force Base

Temperature 695°K (235 F)

TEST TYPE Single high-efficiency filter

Pressure ambient

DATE September 3, 1980

H_2O concentration 3.2%

TIME 1436

Molecular weight 30

SAMPLED VOLUME 8.45 DSCF

Sampled volume 12.28 acf

PROCESS RATE 95% Power 7500#/hr.

Sampling time 10 min

PARTICULATE WEIGHT GAIN : Gelman Filter

Impactor:

Coating:

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{Log } d_p$ (mg/m³)
1		141.64	142.52	0.88	
2					
3					
4					
5					
6					
7					

Diffusion Classifier:

Coating:

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{Log } d_p$ (mg/m³)
1					
2					
3					
4					
5					

TOTAL weight collected in run ______ mg

Concentration 3.680 mg/dscm³

______ grains/dscf

*Note: This filter run immediately prior to Run No. 6 during same engine test.

Field Data Run No. 6

SAMPLING CONDITIONS:

TEST LOCATION Tydall Air Force Base

TEST TYPE Impactor/D.B.

DATE September 3, 1980

TIME 1439

SAMPLED VOLUME 12.49 SCF

PROCESS RATE 95% Power 7500#/hr.

Temperature 690°R (230°F)

Pressure ambient

H_2O concentration 3.2%

Molecular weight 30

Sampled volume 17.50 acf

Sampling time 30 min

PARTICULATE WEIGHT GAIN

Impactor: University of Washington

Coating: Apiezon L

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{ Log } d_p$ (mg/m^3)
1	31	966.69	966.70	0.01	-
2	14	974.85	974.69	-0.16	-
3	5.2	971.05	971.00	-0.05	-
4	2.6	980.08	980.03	-0.05	-
5	1.5	989.54	989.51	-0.03	-
6	0.74	1007.81	1007.86	0.05	-
7	0.38	988.95	988.93	-0.02	-
Impactor Sum (>0.38 μm)				?	

Diffusion Classifier: A

Filter Media: Glass fiber filters with teflon® backup filters and spacing ring liners.

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{ Log } d_p$ (mg/m^3)
1	0.27	141.63	141.56	-0.07	-
2	0.14	135.39	135.55	0.16	-
3	0.069	138.85	138.98	0.13	-
4	0.041	139.14	139.45	0.31	-
5	<0.041	135.86	136.06	0.21	-
Diffusion Classifier Sum (<0.38 μm)				1.05	

TOTAL weight collected in run ______ mg

Concentration ______ mg/dscm

______ grains/dscf

*Note: Teflon filters weighed separately before and after run with average weight change = 0.022 mg.

Field Data Run No. 7

SAMPLING CONDITIONS:

TEST LOCATION Tyndall Air Force Base

TEST TYPE Single hi-efficiency filter

DATE September 4, 1980

TIME 0825

SAMPLED VOLUME 8.13 DSCF

PROCESS RATE 100% Power 12000#/hr.

Temperature 798°R (338°F)

Pressure ambient

H_2O concentration 4.0%

Molecular weight 30

Sampled volume 13.06 acf

Sampling time 10 min

PARTICULATE WEIGHT GAIN : Gelman Filter

Impactor:

Coating:

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{Log } d_p$ (mg/m³)
1		140.05	142.82	2.77	
2					
3					
4					
5					
6					
7					

Diffusion Classifier:

Coating:

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{Log } d_p$ (mg/m³)
1					
2					
3					
4					
5					

TOTAL weight collected in run ______ mg

Concentration 12.039 mg/dscm³

______ grains/dscf

Note: This filter run immediately prior to Run No. 8 in same engine test.

Field Data Run No. 8

SAMPLING CONDITIONS:

TEST LOCATION Tyndall Air Force Base

Temperature 806°R (346°F)

TEST TYPE Impactor/D.B.

Pressure ambient

DATE September 4, 1980

H_2O concentration 4.0%

TIME 0848

Molecular weight 30

SAMPLED VOLUME 5.89 SCF

Sampled volume 9.86 acf

PROCESS RATE 100% Power 12000#/hr.

Sampling time 15 min

PARTICULATE WEIGHT GAIN

Impactor: University of Washington

Coating: Glass Fiber Substrates

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{Log } d_p$ (mg/m^3)
1	31	841.29	841.33	0.04	-
2	14	1228.88	1229.41	0.53	-
3	5.2	1232.21	1232.25	0.04	-
4	2.6	1228.72	1228.74	0.02	-
5	1.5	1215.77	1215.84	0.07	-
6	0.74	123040	1230.46	0.06	-
7	0.38	1225.99	1226.16	0.17	-
Impactor Sum (>0.38 μm)				0.93	

Diffusion Classifier: A

Filter Media: Glass Fiber Filter with teflon® Backup filter and teflon ring liners.

Stage	Stage Cutpoint (μm)	Initial Weight (mg)	Final Weight (mg)	Weight Gain (mg)	$\Delta W/V\Delta \text{Log } d_p$ (mg/m^3)
1	0.27	317.16	317.14	-0.02	-
2	0.14	321.69	321.58	-0.11	-
3	0.069	318.52	318.47	.05	-
4	0.041	322.90	323.11	0.21	-
5	<0.041	318.61	318.78	0.17	-
Diffusion Classifier Sum (<0.38 μm)				0.85	

TOTAL weight collected in run ______ mg

Concentration ______ mg/dscm

______ grains/dscf

*Note: Glass fiber and teflon® filter parts weighed simultaneously.
Note: Glass fiber filter stuck to ring because it wasn't untightened while hot.

APPENDIX C

PET COMPUTER PRINTOUT AND PROGRAM FOR DIFFUSION CLASSIFIER DATA REDUCTION

DIFFUSION CLASSIFIER

```
DIA      WT  %<DIA+....+....+....+....+....+
(MICRON)
0.006    2.63    .04      ##
0.008    3.84   2.07      ##
0.012    7.30   5.03      ###
0.018   14.95  10.65      #####
0.027   24.23  22.15      ####0##
0.039   25.82  40.79      ####0##
0.057   19.15  60.65      #####0#
0.083   11.78  75.38      ####
0.121    7.02  84.44      ###
0.176    4.42  89.84      ##
0.255    3.04  93.25      ##
0.371    2.29  95.59      ##
0.538    1.86  97.34      #
0.782    1.59  98.78      #

OBSERVED    130   81.17   57.86   34.7   19.8

CALCULATED 129.9   81   57.6   34.6   19.7
LOGRATIO   2.67340513E-04  4.89390909E-04  1.30791932E-03  1.258144E-04  1.29398
03E-03
RMSE= 8.[illegible]07988E-04
GEO MEAN DIA= .03535048 2
GEO STD DEV= 2.55383482
```

```
FLOW IN L/MIN= 12.3
TEMPERATURE IN KELVIN= 375
TOTAL PRESSURE IN MM HG= 760
SCREENS STAGE 4= 5
SCREENS STAGE 3= 10
SCREENS STAGE 2= 20
SCREENS STAGE 1= 36
ASSUME INPUT WEIGHT ON STAGE 5=100%
% WT ON STAGE 4= 62.4384616
% WT ON STAGE 3= 44.5076923
% WT ON STAGE 2= 26.6923077
% WT ON STAGE 1= 15.2307692


READY.

 10 DIM DC(5),RA(5)
 20 DIM CH(20),DX(5),DP(5,20),CC(5)
 30 DIM SZ(20),P(5,20),C(5),PC(20),PL(20),PK(20)
 40 INPUT "FLOW IN L/MIN=";Q
 50 INPUT "TEMPERATURE IN KELVIN=";T
 60 INPUT "TOTAL PRESSURE MM HG=";P
 70 INPUT "SCREENS STAGE 4=";W
 80 INPUT "SCREENS STAGE 3=";X
 90 INPUT "SCREENS STAGE 2=";Y
 100 INPUT "SCREENS STAGE 1=";Z
 110 REM     NZ IS THE NUMBER OF SIZE CLASSES
 120 NZ=14
 130 REM     INITIALIZATION OF SIZE CLASSES
 140 SZ(1)=5.0E-07
 150 FOR I=2 TO NZ
 160 SZ(I)=SZ(I-1)*1.452134
 170 NEXT I
 180 REM     CALC VISCOSITY
 190 T5=T↑1.5
 200 T7=.068*T+7.8
 210 V4=T5/T7
 220 V4=V4*1.0E-06
 230 REM     CALC GAS DENSITY
 240 T4=4.645592E-04
 250 R4=T4*P/T
 260 REM     CALC MEAN FREE PATH
 270 RN=3.70104E-04
 280 TN=.499*R4
 290 LB=(V4*RN/TN)/T↑.5
 300 FOR I=1 TO NZ
 310 REM     CALC CUNNINGHAM'S CORRECTION
 320 TE=2.*LB/SZ(I)
 330 SL=-.55*SZ(I)/LB
 340 KR=1.257+.4*EXP(SL)
 350 CE=1.+TE*KR
 360 REM     CALC DIFFUSIVITY
```

```
370 BI=1.371E-16*T*CE
380 BA=9.4247777*V4*SZ(I)
390 DF=BI/BA
400 REM    CALC PECLET NUMBER
410 QU=.125333333*Q
420 QO=45.603673*DF
430 R5=-3.01
440 G5=-.59
450 RP=R5*(QU/QO)↑G5
460 IF RP<-2.1 THEN RP=-2.1
470 REM    CALC PENETRATIONS  BASED ON RANGARAJ CALIBRATION EQUATION
480 P(1,I)=1.
490 WR=W*RP
500 P(2,I)=EXP(WR)
510 XR=X*RP
520 P(3,I)=EXP(XR)
530 YR=Y*RP
540 P(4,I)=EXP(YR)
550 ZR=Z*RP
560 P(5,I)=EXP(ZR)
570 NEXT I
580 REM    NA IS THE NUMBER OF STAGES
590 NA=5
600 NT=NA-1
610 YY=Y
620 FOR J=1 TO NZ
630 REM    CALC DIFFERENCES IN PENETRATION
640 FOR I=1 TO NT
650 DP(I,J)=P(I,J)-P(I+1,J)
660 NEXT I
670 DP(NA,J)=P(NA,J)-0
680 NEXT J
690 REM    FOR EACH STAGE FINDS MAXIMUM VALUE OF DP
700 FOR I=1 TO NA
710 DX(I)=0.0
720 FOR J=1 TO NZ
730 IF DX(I)>DP(I,J) GOTO 790
740 DX(I)=DP(I,J)
750 DH=1.0E+30:DL=1.0E-30
760 Y=SGN(DX(I)):DA=ABS(DX(I))
770 IF DA<=DL THEN DX(I)=Y*DL
780 IF DA>DH THEN DX(I)=Y*DH
790 NEXT J
800 NEXT I
810 REM    INPUT STAGE WEIGHTS
820 INPUT "WT ON STAGE 5=";C(1)
830 INPUT "WT ON STAGE 4=";C(2)
840 INPUT "WT ON STAGE 3=";C(3)
850 INPUT "WT ON STAGE 2=";C(4)
860 INPUT "WT ON STAGE 1=";C(5)
```

```
870 REM     GIVES EQUAL INITIAL WEIGHT TO EACH SIZE CLASS
880 FOR J=1 TO NZ
890 PC(J)=C(1)/NZ
900 NEXT J
910 REM     CALC WEIGHT DIFFERENCES BETWEEN STAGES
920 FOR I=1 TO NT
930 DC(I)=C(I)-C(I+1)
940 NEXT I
950 DC(NA)=C(NA)
960 REM     LINES 980-1160 ARE TWOMEY'S NON-LINEAR TECHNIQUE
970 REM     K IS THE NUMBER OF ITERATIONS THROUGH THE ALGORITHM
980 FOR K=1 TO 40
990 FOR J=1 TO NZ
1000 CH(J)=PC(J)
1010 NEXT J
1020 FOR I=1 TO NA
1030 Z1=0.0
1040 FOR J=1 TO NZ
1050 Z1=Z1+DP(I,J)*PC(J)
1060 NEXT J
1070 Y=SGN(T1)
1080 IF Z1=0.0 THEN Z1=Y*DL
1090 T1=DC(I)/Z1-1.
1100 FOR J=1 TO NZ
1110 IF DX(I)=0. THEN DX(I)=DL
1120 T2=1.0+T1*DP(I,J)*.8/DX(I)
1130 PC(J)=PC(J)*T2
1140 NEXT J
1150 NEXT I
1160 NEXT K
1170 REM     LINES 1180-1300 CALCULATES CUMULATIVE WEIGHT PERCENTS
1171 REM     AND NORMALIZES DISTRIBUTION TO STAGE 5
```

```
1180 SM=0.
1190 FOR J=1 TO NZ
1200 SM=SM+PC(J)
1210 NEXT J
1220 FOR J=1 TO NZ
1230 PK(J)=INT(PC(J)*100*100/SM)/100
1240 PC(J)=INT(PC(J)*100*C(1)/SM)/100
1250 NEXT J
1260 LET R=NZ-1
1270 PL(NZ)=100-PK(NZ)
1280 FOR J=1 TO R
1290 PL(NZ-J)=PL(NZ-J+1)-PK(NZ-J)
1300 NEXT J
1310 OPEN 1,4
1320 CMD 1
1330 PRINT CHR$(1)"DIFFUSION CLASSIFIER"
1340 PRINT:PRINT:PRINT
1350 T$="DIA  WT %<DIA"
1360 PRINT CHR$(1)T$;CHR$(129)TAB(5);:GOSUB2040 :PRINT
1370 PRINT "(MICRON)       "
1380 OPEN 3,4,2
1390 OPEN 2,4,1
1400 FOR J=1 TO NZ
1410 II=25.*PC(J)/100.+.5
1420 IF II<=25 GOTO 1440
1430 II=25
1440 PJ=PC(J)
1450 PL=PL(J)
1460 SJ=SZ(J)*1.0E+07
1470 PL=(INT(100*PL))/100
1480 SJ=(INT(SJ*122.6067))/100
1490 SJ=SJ/1000
1500 PRINT#3,"Z.999    99.99    99.99"
1510 PRINT#2,SJ;PJ;PL;
1520 PRINT#1,"           I";:GOSUB2110:PRINT#1
1530 NEXT J
1540 CLOSE 2
1550 OPEN 4,4
1560 CMD 4
1570 PRINT CHR$(1)"OBSERVED  ";:GOSUB2210:PRINT
1580 FOR I=1 TO NA
1590 REM    CHANGES RAW STAGE WEIGHTS TO PERCENTS
1600 CP(I)=C(I)*100/C(1)
1610 REM    COMPUTES "CALCULATED" CUMULATIVE WEIGHTS ON STAGES
1620 CC(I)=0.0
1630 FOR J=1 TO NZ
1640 CC(I)=CC(I)+P(I,J)*PC(J)
1650 NEXT J
1660 REM    CALC LOGRATIO
1670 RA(I)=LOG(C(I)/CC(I))/2.302585
```

```
1680 S1=S1+RA(I)↑2
1690 NEXT I
1700 PRINT CHR$(1)"CALCULATED";:GOSUB2250:PRINT
1710 PRINT"LOGRATIO  ";:GOSUB2300:PRINT
1720 REM     CALC RMSE BETWEEN "OBSERVED" AND "CALCULATED"
1730 RM=SQR(S1/NA)
1740 REM     CALC MMD AND GEO STD DEV
1750 S1=0.:S2=0.
1760 FOR J=1 TO NZ
1770 SS=LOG(SZ(J))
1780 S1=S1+SS*PC(J)
1790 S2=S2+SS*SS*PC(J)
1800 NEXT J
1810 S1=S1/CC(1)
1820 S2=S2/CC(1)
1830 S2=SQR(S2-S1*S1)
1840 S1=EXP(S1)
1850 S2=EXP(S2)
1860 S1=S1*1.0E+04
1870 PRINT "RMSE=";RM
1880 PRINT CHR$(1)"GEO MEAN DIA=";S1
1890 PRINT CHR$(1)"GEO STD DEV=";S2
1900 PRINT:PRINT:PRINT
1910 PRINT "FLOW IN L/MIN=";Q
1920 PRINT "TEMPERATURE IN KELVIN=";T
1930 PRINT "TOTAL PRESSURE IN MM HG=";P
1940 PRINT "SCREENS STAGE 4=";W
1950 PRINT "SCREENS STAGE 3=";X
1960 PRINT "SCREENS STAGE 2=";YY
1970 PRINT "SCREENS STAGE 1=";Z
1980 PRINT "ASSUME INPUT WEIGHT ON STAGE 5=100%"
1990 PRINT "% WT ON STAGE 4=";CP(2)
2000 PRINT "% WT ON STAGE 3=";CP(3)
2010 PRINT "% WT ON STAGE 2=";CP(4)
2020 PRINT "% WT ON STAGE 1=";CP(5)
2030 GOTO 2340
2040 PRINT"+";
2050 FOR I=1 TO 25
2060 F$="."
2070 IF I/5=INT(I/5) THEN F$="+"
2080 PRINT F$;
2090 NEXT I
2100 RETURN
2110 AA=INT(II)
2120 PRINT#1,"           ";
2130 IF AA<1 THEN GOTO 2190
2140 FOR I=1 TO AA
2150 G$="#"
2160 IF I/5=INT(I/5) THEN G$="0"
```

```
2170 PRINT#1,G$;
2180 NEXT I
2190 PRINT#1,"#";
2200 RETURN
2210 FOR I=1 TO NA
2220 PRINT C(I);
2230 NEXT I
2240 RETURN
2250 FOR I=1 TO NA
2260 CO=(INT(10*CO(I)))/10
2270 PRINT CO;
2280 NEXT I
2290 RETURN
2300 FOR I=1 TO NA
2310 PRINT RA(I);
2320 NEXT I
2330 RETURN
2340 PRINT#4:CLOSE 4
2350 END
```